Quasistationary supercooled (recombining) plasma produced by an electron beam in a dense gas

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Experiments are described in which a low-temperature helium plasma that recombines in a nonstationary manner has been produced for the first time. The state of this plasma differs from thermodynamic equilibrium in that the free electrons are strongly supercooled. The plasma density ($N_e \approx 5\times10^{15}$ cm^{-3}) at the measured electron temperature ($T_e = 0.3$–0.4 eV) and at a given density of the neutral atoms of the gas ($N_0 \approx 2\times10^{18}$ cm^{-3}) is larger by many orders of magnitude than that of a plasma in thermodynamic equilibrium [corresponding to the Saha formula (1)], and the electron temperature is correspondingly lower than the thermodynamic-equilibrium temperature corresponding to the measured plasma density. This plasma state was obtained in the active zone of a "burning" beam discharge and was maintained quasistationary by passing a hard electron beam (electron energy 10 keV, current 10–100 A, diameter ~ 1 cm) through dense helium (helium pressure $p \approx 50$–100 mm Hg). The recombination nonequilibrium state of the quasistationary plasma with supercooled electrons, realized in the described experiment, is the opposite of the ionization nonequilibrium state of all types of "nonbeam" gas discharges, in the active zones of which the electrons are always superheated (to a lesser or greater degree). A method of producing a quasistationary supercooled plasma and a spectroscopic diagnostic procedure for it are described.

INTRODUCTION

We describe in this paper experiments in which the state of quasistationary supercooling of electrons of a dense low-temperature weakly ionized plasma has been realized for the first time. This called for the use of a new form of gas discharge, different from the one previously employed, and for the satisfaction of a number of nontrivial conditions. We shall consider these conditions before we describe the experimental setup.

We start with the main definitions. An equilibrium plasma is defined as one in which the tmperature of the Maxwellian distribution of its free electrons (T_e) is equal to the thermodynamic-equilibrium temperature (T_{eq}), which is connected with the concentration of the plasma electrons (N_e) and of the atoms in the ground state (N_0) by the Saha formula

$$N_e^2 \approx 3\cdot10^{21}\frac{g_i}{g_0}N_0T_p^{3/2}\exp\left(-\frac{J}{T_{eq}}\right), \qquad (1)$$

where J is the ionization potential of the atoms (J and T_{eq} are given in eV), and g_i and g_0 are the statistical weights of the ground states of the ion and of the atom of the gas. For example, in the case of a helium plasma ($g_i/g_0 = 2$) with $N_e = 10^{16}$ cm^{-3} and $N_0 = 10^{18}$ cm^{-3} we get from (1) $T_{eq} \approx 1.4$ eV; in the case of a hydrogen plasma ($g_i/g_0 = 1/2$) we have under the same conditions $T_{eq} \approx 0.85$ eV, etc. To determine the character of the state of the plasma we apply the following criteria.

1) We measure the plasma parameters T_e, N_e, and N_0; formula (1) is used to calculate the thermodynamic-equilibrium temperature T_{eq} corresponding to the measured concentrations N_e and N_0. We compare the calculated value of T_{eq} with the measured electron temperature T_e. If $T_e \neq T_{eq}$, we call the plasma nonequilibrium; at $T_e > T_{eq}$ and $T_e < T_{eq}$ we call the plasma superheated and supercooled, respectively.

2) We substitute the measured electron temperature T_e for T_{eq} in (1) and calculate the corresponding thermodynamic-equilibrium plasma concentration. If the calculated concentration turns out to be lower than the measured one, then the plasma with the measured values of T_e, N_e, and N_0 is supercooled.

Thus, in a supercooled plasma, the concentration of the charged particles N_e exceeds the thermodynamic-equilibrium value corresponding, in accordance with the Saha formula (1), to the measured values of T_e and N_0 (it will be shown below that under the experimental conditions the difference between N_e and the equilibrium value reaches many orders of magnitude). Such a plasma (with "excess" concentration) is predominantly recombining: the ionization by the plasma particles does not balance their recombination. The production of such a plasma is of interest for the investigation of recombination kinetics[2], collision-induced electronic transitions in atoms, the construction of recombination (plasma) lasers[3]1), etc.

It is interesting to note one more property of a supercooled plasma: the concentration N_n of strongly excited atoms in this plasma exceeds the thermodynamic-equilibrium value $(N_n)_{eq}$, determined by the Boltzmann formula

$$(N_n)_{eq} = N_0\frac{g_n}{g_0}\exp\left(-\frac{E_n}{T_{eq}}\right), \qquad (2)$$

where E_n and g_n are the excitation energy and the statistical weight of the considered state of the atom. In fact, regardless of the ratio of the quantities T_e and T_{eq}, the populations of the states of atoms with energy E_n sufficiently close to the ionization potential are connected with the concentration N_e of the free plasma electrons and their temperature T_e by the relation[4]

$$N_n \approx 1.5\cdot10^{-22}\frac{g_n}{g_i}N_e^2T_e^{-3/2}\exp\left(\frac{J-E_n}{T_e}\right), \qquad (3)$$

where T_e, E_n, and J are in electron volts.

In a thermodynamic-equilibrium plasma ($T_e = T_{eq}$), relation (3) is fully equivalent to formulas (1) and (2); the values of N_n from (3) and $(N_n)_{eq}$ from (2) are therefore the same for a given energy E_n. In a supercooled plasma at a given value of N_e, we have the inequality $T_e < T_{eq}$, and therefore, according to (3), the concentration N_n of the excited atoms exceeds the equilibrium value $(N_n)_{eq}$. As will be shown below, the difference between N_n and $(N_n)_{eq}$ can reach many orders of magnitude, which is of interest, in particular, for plasma chemistry. Relation (3) (which we shall not call the Saha formula, in order not to confuse it with formula (1)) is valid for states with sufficiently large values n of the principal quantum number ($n \geq n_c$). The threshold value n_c in an equilibrium plasma is equal to unity; in a non-equilibrium plasma it depends on N_e and T_e: thus, in the range of parameters $N_e \gtrsim 10^{15}$ cm^{-3} and $T_e \approx 0.3-0.6$ eV we have $n_c \lesssim 4$[4].

We now proceed to the formulation of the problem. If we apply the criterion formulated here for the supercooling of the plasma electrons to the conditions of the experiments performed to date, then it is easy to verify that some of them were performed under conditions of supercooling of the plasma electrons in the active zone of the gas discharge[4a,b]. These conditions were realized, however, during the short stage of plasma decay in the afterglow of a pulsed discharge. Unlike all preceding investigations, we deal here with supercooling of plasma electrons in the active zone of the discharge over its entire duration, in principle in a stationary regime. The plasma state investigated here is in essence stationary. Nonetheless, we shall use the prefix "quasi" for its description, inasmuch as for technical reasons the plasma is produced by single pulses of ~0.3 msec duration. The plasma lifetime, however, is much larger than the characteristic density and temperature relaxation times of the plasma particles.

1. CONDITIONS FOR THE FORMATION OF A STATIONARY SUPERCOOLED PLASMA

Let us formulate the conditions under which the considered plasma is produced.

1. To obtain a quasistationary supercooled plasma, none of the gas-discharge forms employed at present as effective generators of a dense low-temperature plasma will do, including arc discharge, high-frequency and optical plasmatrons, pinches, discharge tubes, etc. (see[5]). The proof of this statement consists in the following. The plasma is in thermodynamic equilibrium if the conditions for its formation and decay are mutually reversible, i.e., if, for example, (stepwise) ionization of the gas atoms (A) by the plasma electrons is practically balanced by the impact three-particle recombination of these electrons with the ions (A^+):

$$A^{+}+e+e \rightleftharpoons A^{*}+e. \tag{4}$$

On the other hand, if the plasma decay is determined essentially not only by process (4) but also, for example, by radiative recombination (in the absence of reabsorption) or by diffusion, then the temperature of the plasma electrons must of necessity be higher than the thermodynamic-equilibrium value, in order to replenish the additional losses of particles and energy from the plasma. Therefore the plasma in the active zone of a gas discharge can be (and is indeed) superheated, $T_e \gtrsim T_{eq}$, but cannot be supercooled (which calls for $T_e < T_{eq}$).

2. To obtain a quasistationary supercooled plasma it is necessary that the plasma-production function be performed not by the plasma electrons but by some external ionizer, for example an electron beam. The beam can be introduced into the plasma from the outside or produced inside the plasma with the aid of a strong electric field; in either case the beam electrons are external with respect to the energy distribution of most charged particles (this distribution is assumed Maxwellian in this article). However, this necessary condition is far from sufficient. In fact, it follows from very numerous experiments that a plasma in which an intense electron beam propagates turns out to be not only strongly superheated, but in general of high temperature ($T_e > J$), since the plasma electrons are effectively heated in the electric field of the plasma oscillations excited by the electron beam (see, e.g.,[6]). To eliminate this effect it is necessary first that the frequency (ν) of the electron collisions leading to loss of momentum (i.e., collisions with one another and with the ions and atoms of the gas) exceed the "hydrodynamic" increment (γ) of the plasma oscillations. In the case of electron Langmuir (the most dangerous oscillations, the indicated condition is

$$N_0\langle\sigma_{el} v_e\rangle+N_e\langle\sigma_C v_e\rangle > \left(\frac{N_1}{N_e}\right)^{1/3}\left(\frac{4\pi N_e e^2}{m}\right)^{1/2}, \tag{5}$$

where v_e is the velocity of the plasma electron, σ_{el} and σ_C are the effective cross sections for the loss of momentum by the plasma electron following its elastic and Coulomb collisions, respectively, with the gas and plasma particles, N_1 is the density of the beam electrons, m and e are the mass and charge of the electron, and the angle brackets denote averaging over the energy (Maxwellian) distribution of the plasma electrons. However, even the satisfaction of condition (5) does not fully exclude strong heating of the electrons in plasma oscillations, owing to the existence of dissipative instability of a beam plasma with respect to buildup of electron oscillations with frequencies and increments that are smaller than (or of the order of) those of Langmuir oscillations[7]. In order for this instability not to arise, the beam electrons must have not too small a velocity scatter (under the experimental conditions discussed below, this scatter is of the order of several percent of the average velocity)[7].

3. If the conditions indicated in Sec. 2 are satisfied then the "beam" plasma will be low-temperature ($T_e < J$). In order for it to be supercooled in this case, it is necessary to satisfy one more condition, namely, the secondary electrons produced when the gas is ionized by the beam (and having, as is well known, an energy on the order of the ionization potential J) should lose their energy sufficiently rapidly in elastic collisions with atoms and ions. "Sufficiently rapidly" means within a time τ_{cool} much smaller than the characteristic time τ_p of plasma production:

$$\tau_{cool} \approx \left[2\frac{m}{M}(N_0\langle\sigma_{el} v_e\rangle+N_e\langle\sigma_C v_e\rangle)\right]^{-1} \ll \tau_p=\frac{N_e}{N_1 N_0 \sigma_1 v_1}, \tag{6}$$

where M is the mass of the gas atom (ion), σ_1 is the cross section for the ionization of the gas by beam electrons having a velocity v_1 $\langle\sigma_C v_e\rangle \approx 2\times10^{-5}/T_e^{3/2}$ [eV] is the rate coefficient of momentum loss by a plasma electron of energy $\sim T_e$ in collisions with the plasma particles[8]. The electron temperature is determined in this case by a relation that reflects the equality of the energy acquired by the electrons produced by the beam in the gas to the energy given up by them to the heavy particles (atoms and ions):

$$\Delta T_e=T_e-T \approx J N_0 N_1 \sigma_1 v_1 \left[2\frac{m}{M}N_e(N_0\langle\sigma_{el} v_e\rangle+N_e\langle\sigma_C v_e\rangle)\right]^{-1}, \tag{7}$$

where T is the gas temperature. For the ion temperature (T_i) we easily obtain analogously $\Delta T_i \equiv T_i - T \ll T_e - T$, i.e., as assumed in (7), $T_i \approx T$. The gas temperature T is assumed fixed and sufficiently small (see below). It follows from (7) that if the inequality (6) is strong enough, then the plasma turns out to be supercooled ($T_e < T_{eq}$).

4. In order for the gas temperature (together, accord-

ing to (7), with the electron temperature) not to rise above the permissible level, the heat released in the gas as a result of the ionization energy lost by the beam electrons should be diverted rapidly to the periphery of the discharge (to cooled walls). If the beam ionization-loss power does not exceed a certain limit, then the stabilization of the gas temperature at a sufficiently low level (under our conditions, for example, $T \lesssim 0.2$ eV) can be attained by means of classical dissociative thermal conductivity[1b,9].

To illustrate the significance of the formulated conditions for a particular experiment, we make a few numerical estimates. We start for the sake of argument with supercooled-plasma parameters corresponding to the proposed operating conditions of a stationary recombination laser[3]:

$$N_e \approx 10^{15}\,\text{cm}^{-3},\ T_e \approx 0.3 \div 0.4\,\text{eV}\,(T_e < T_{eq}),\ N_0 \approx 10^{18} \div 10^{19}\,\text{cm}^{-3}, \quad (8)$$

with helium as the working gas, plasma length ~100 cm, and the plasma situated in a magnetic field $H = (2-3) \times 10^3$ Oe, along which an electron beam propagates. The beam parameters needed to form the plasma are determined by the ratio of the balance between the ionization of the gas by the beam and impact (triple) recombination of the plasma (it is easy to verify that under the indicated conditions the diffusion decay of the plasma can be neglected):

$$N_1 N_0 \sigma_1 v_1 = \alpha(T_e) N_e^2 = \beta(T_e) N_e^3, \quad (9)$$

where $\beta(T_e)$ is the impact-recombination coefficient and decreases rapidly with increasing electron temperature; at the temperature $T_e \approx 1/3$ eV (which is of greatest interest for the exposition that follows) we have $\beta \approx 4 \times 10^{-26}$ cm^6 sec^{-1}[2a]. For the conditions (8) it is necessary, for example, to have an electron beam of energy $W_1 \approx 10-20$ keV ($\sigma_1 \approx (1-2) \times 10^{-18}$ cm^2)[10] and a current density $j_1 = N_1 e v_1 \approx 10$ A/cm^2, with $N_1 \approx 10^{10}$ cm^{-3}. Since $\sigma_{el} \approx 5 \times 10^{-16}$ cm^2 [11], condition (5) for the nonexcitation of Langmuir oscillations is satisfied.

Under the conditions (8), the ionization mean free path of the beam electrons in the gas is approximately equal to the length of the apparatus. Since, as is well known,[12] the electrons are scattered more strongly than they lose energy, the scatter of the (longitudinal) beam velocity will be more than sufficient under these conditions to stabilize the dissipative instability indicated above[7]. Consequently, there will be no heating of the electrons by the plasma oscillations. The time of cooling of the plasma electrons under the conditions of (8) is $\sigma_{cool} \approx 10^{-2}\,\tau_p$, i.e., a plasma having the indicated parameters will be appreciably supercooled, as can be seen from (1). Thus, to obtain a supercooled plasma it is necessary to provide a rather nontrivial experimental situation; in particular, it is necessary to ensure a quasistationary gas pressure drop of 7–8 orders of magnitude between the working volume (where $p \approx 10^2$–10^3 mm Hg) and the region of the electron gun (where $p \approx 10^{-5}$ mm Hg).

2. EXPERIMENTAL SETUP

In the formulation of the problem we started from the aim of obtaining a quasistationary plasma, and therefore confined our choice to beams of moderate power: electron energy on the order of several dozen keV, current on the order of several dozen amperes, and a beam cross section ~1 cm^2. To make full use of the beam energy, the length (L) of the working volume of the apparatus should be practically equal to the ionization mean free path of the beam electrons:

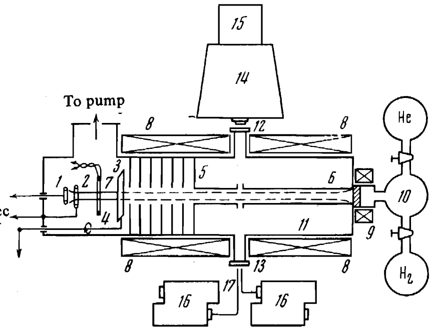


FIG. 1. Experimental installation: 1, 2—cathode and accelerating electrons of the electron gun; 3—swing-away electrode to control the beam current; 4—Rogowski loop; 5—gas-filled delay line; 6—working volume (copper tube of 3.2 cm diameter with openings for the plasma diagnostics); 7—electron beam; 8—magnetic-field coil; 9—electromagnetic gas valve; 10—volume for gas mixing (He-H$_2$); 11—vacuum chamber; 12 & 13) diagnostic windows of optical glass; 14—STÉ-1 spectrograph; 15—polychromator attachment based on fiber optics; 16—DMR-4 monochromators; 17—light pipes.

$$L \approx W_1/N_0\sigma_1\Delta W, \quad \Delta W \approx 30-40\ \text{eV}; \quad (10)$$

under conditions (8), the length is $L \approx 10^2$ cm. We note that the considered beam regime differs in principle from the beam-plasma discharge regime[6] in which, owing to the small gas pressure ($p \lesssim 10^{-3}$ mm Hg), the beam energy is consumed mainly in excitation of electronic plasma (Langmuir) oscillations, i.e., in the production of a high-temperature plasma with a strongly superheated electronic component ($T_e \approx 10^2$ eV $\gg J$). The experimental installation[13] (Fig. 1) consists of four principal elements: the working volume 6, which is the interior of a copper tube 3.2 cm in diameter and 100 cm long, an electron gun 1, 2 fed from a 3×10^{-6} F capacitor, an intermediate unit 5 ensuring the required pressure drop between the working volume and the gun, and a solenoid 8 that produces a time-constant magnetic field of intensity H up to $(5-6) \times 10^3$ kOe. The electron beam is turned on by single rectangular pulses. The interval between pulses is ~3 min. The beam pulse duration is limited by the arrival of plasma particles into the gun region and amounts to several hundred microseconds, which exceeds by 2 or 3 orders of magnitude the characteristic plasma recombination time ($\tau_{rec} = 1/\beta N_e^2$). The beam conditions are therefore quasistationary; they are physically equivalent to the stationary regime, but their technical realization is incomparably simpler.

The gas pressure in the working volume (~800 cm^{-3}) is regulated with the aid of an electromagnetic gas valve 9 and can reach ~100 mm Hg. The gas valve is turned on by single pulses synchronized with the electron-beam pulses: the voltage on the electron gun (the cathode of which is heated beforehand to the required temperature) is applied with a delay of 5 msec after the application of the "opening" voltage to the valve; this leaves enough time for the gas to fill the entire length of the working volume. The working gas is helium, to which a controllable amount of hydrogen is added to stabilize the gas temperature via the indicated dissociative thermal conductivity and for spectral diagnostics of the plasma with the aid of the Balmer lines. The hydrogen in a recombination laser[3] operating with a helium plasma can also perform the function of predominant depletion of the lower level of the laser transition.

In the tube that limits the working volume, at a distance 25 cm from its starting point (on the side of the electron gun), there are two diametrically opposite equal slots 0.4 cm wide (the dimension along the tube generatrix) and 2 cm long (in azimuth); the plasma glow is examined through these openings for the purpose of spectroscopic diagnostics of its parameters.

The intermediate unit 5 is a gas-filled delay line[14]. The time constant of this line, which is determined by the time required to fill it with the working gas, amounts to ~15 msec under the gas-intake conditions indicated above. The line delays, by this time interval, the arrival of the bulk of the working gas at the region of the electron gun, and by the same token makes it possible to effect during the duration of the beam pulse (several hundred microseconds) the required pressure drop, by seven to eight orders of magnitude, between the working volume and the electron gun.

The longitudinal magnetic field (which is constant in time and is produced by coils 8) is used to improve the control of the electron beam, and also to prevent the spilling out of the beam electrons on to the walls of the working volume as the result of the strong (Coulomb) scattering of the beam electrons by the nuclei of the working-gas atoms. The magnetic field is made inhomogeneous along the installation to decrease the beam diameter in the working volume, where it is approximately five times larger than in the region of the electron gun and at the exit from the working volume.

The gun has a directly heated cathode 1 in the form of a ring 2.2 cm in diameter of tungsten wire 1.2 mm in diameter. The accelerating electrode of the gun is a tantalum ring 2 of 4.5 cm diameter of wire 2 mm in diameter, located 1.3 cm away from the cathode. During the time of the pulse, a negative potential 10–20 kV is applied to the gun cathode, and the accelerating electrode has the potential of the (grounded) walls of the working volume. The electron-beam current at the exit from the gun is measured with the Rogowski loop 4. Independent and direct measurements of the gun current are made with the aid of a swing-away receiving electrode of area 6×8 cm^2, made of a molybdenum plate 2 mm thick. The results of the measurement of the beam by two methods coincide exactly. The gun section is evacuated with an oil diffusion pump with an effective delivery $\sim 1.5 \times 10^3$ liter/sec, the residual pressure in the section is $\sim 1 \times 10^{-6}$ mm Hg, and in the course of the regular operation of the gas valve it is $\sim 1 \times 10^{-5}$ mm Hg. The electron-beam diameter in the working volume is ~1 cm, the magnetic field decreases beyond the working volume, and the beam expands again.

With respect to the choice of helium as the working gas, it is important to note the following. It might seem that since hydrogen is introduced in one way or another into the system, it would be logical to use it as the main working gas, all the more since, according to (5), the small mass of the hydrogen molecules and ions would contribute to a minimal deviation of the plasma electron temperature from the gas temperature. Nonetheless, we preferred helium because in the case of molecular hydrogen the principal ions in the discharge of the investigated type are the molecular ions H_2^+ and H_3^+ [11], which have a very large coefficient of (dissociative) recombination. In such a medium it is very difficult to produce a plasma of the required density. Getting ahead of ourselves, we indicate that in our experiments the maximum plasma density in pure hydrogen did not exceed 10^{14} cm^{-3}. The most suitable among the gases heavier than hydrogen was helium, which had minimal mass (see (5)) and also the minimal recombination coefficient[2]. In virtue of the latter circumstance, the density of the helium plasma in the experiments below reached $\sim 5 \times 10^{15}$ cm^{-3}.

3. PLASMA DIAGNOSTICS

The plasma parameters were measured by contactless spectroscopic methods. The concentration of the plasma electrons was determined from the Stark broadening of the spectral line H_β of the Balmer series of the hydrogen atom (the hydrogen was added to the system in the form of a small impurity). To measure the contour of this line and to plot the temporal evolution of the concentration of the plasma during the beam pulse, we constructed and adjusted a 10-channel polychromator (14, 15) based on fiber optics (see also[15]). It consists of a diffraction spectrograph 14 (STÉ-1, with inverse dispersion 8 Å/mm), and a sectionalized multichannel light pipe placed in its focal plane. The light from the independent panels of this light pipe is distributed among ten FÉU-71 photomultipliers, the signals from which, after passing through 10 emitter followers, were fed through coaxial cables to five two-beam S1-34 oscilloscopes. The polychromator was tuned to the H_β line with the aid of a TVS-15 gas-discharge hydrogen-line source and a specially prepared adjusting mechanism, which made it possible to move the light pipe in the image plane of the spectrograph. The polychromator channels are calibrated in sensitivity by illuminating the input slit of the spectrograph uniformly over its height, using a type K-30 incandescent lamp, and equalizing the signals from all the channels by means of the adjustable load resistors of the photomultiplier. The arrangement and description of the operation of the polychromator are contained in an article written by us (jointly with I. F. Khanov) and scheduled for publication in "Pribory i Tekhnika Éksperimenta" in 1974.

As is well known, the Stark half-width $\Delta\lambda_{1/2}$ (the width at half intensity) of the H_β line is connected with the plasma concentration by the relation

$$\Delta\lambda_{1/2} \approx 2N_e^{2/3}, \qquad (11)$$

where $\Delta\lambda_{1/2}$ is in Å and N_e is in 10^{15} cm^{-3}. At $N_e = 10^{15}$ cm^{-3} we have $\Delta\lambda_{1/2} = 2$ Å, which is equivalent to 250μ or to six neighboring polychromator channels in the focal plane of the spectrograph. The minimal plasma density that can still be measured with this polychromator is $\sim 10^{14}$ cm^{-3}.

Among the other mechanisms of H_β line broadening, the strongest is known[16] to be the Doppler mechanism; it leads to a broadening ~0.2 Å at $T \approx 0.35$ eV. If N_e greatly exceeds 10^{14} cm^{-3} (and it is only this regime, as noted many times, which is of interest to us), then the Doppler broadening of the H_β line is small in comparison with the Stark broadening. The half-width of the apparatus function of the polychromator is 0.4 Å. The "true" half-width $\Delta\lambda_{1/2}$, which is used to calculate the plasma density from (11), is determined by subtracting the sum of the apparatus and Doppler half-widths from the half-width of the measured contour of the H_β line. The measurements show that the contour of the H_β line is symmetrical with respect to its center. We therefore present below halves of the contours plotted with twice as much detail. It should be noted that a check scanning of the vicinity of the H_β line with the aid of the polychromator shows that within the limits of the experimental accuracy there is no interference on the part of any other lines (particularly the line close to H_β produced by radiative recombination of the hydrogen-like ion He^{++}) or of the continuum.

The plasma-electron temperature T_e is determined in the following manner. As already indicated in the introduction, in a plasma with the expected parameters the populations N_n of the hydrogen atom excitation levels with principal quantum numbers $n \geq 4$ are connected with the plasma-electron temperature by Eq. (3), where in the case of hydrogen we have $J - E_n = J/n^2$ and $J = 13.6$ eV. On the other hand, the populations of the considered levels are proportional to the intensities $\epsilon(n)$ of the spectral lines corresponding to the transitions from these levels: $\epsilon(n) = A_n N_n hc/\lambda_n$, where A_n is the Einstein coefficient, λ_n is the transition wavelength, h is Planck's constant, and c is the speed of light. Therefor measurement of the intensity ratio of two spectral lines emitted in spontaneous transitions of the hydrogen atom from pre-continuum excitation levels ($n \geq 4$) makes it possible to determine the temperature of the free electrons of the plasma

$$T_e = J\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)\left[\ln\frac{\varepsilon_1\lambda_1 A_2}{\varepsilon_2\lambda_2 A_1}\right]^{-1}, \qquad (12)$$

where the subscripts 1 and 2 label quantities pertaining to the upper levels of the considered transitions with the smaller and larger values of the principal quantum number, respectively. In our experiments T_e is determined from the intensity ratio of the lines H_β ($n_1 = 4$) and H_δ ($n_2 = 6$) of the Balmer series of the hydrogen atom, corresponding to the transitions ($n = 4$) → ($n = 2$) and ($n = 6$) → ($n = 2$).

Measurement of the relative intensities of the spectral lines was carried out simultaneously with the aid of two DMR-4 monochromators (16), with the light fed to their entrance slits with the aid of the light pipes 17; the signals from the monochromators placed behind the exit slits of the monochromator were fed to an oscilloscope and photographed. The monochromator-system sensitivity was calibrated in wavelength with the aid of an SI-8-200U ribbon-type incandescent lamp placed diametrically opposite to the monochromators, behind diagnostic window 12. The widths of the entrance slits of both monochromators were chosen to be 1 mm (at monochromator inverse dispersions 50 Å/mm and 25 Å/mm in the regions of the lines H_β and H_δ, respectively), and exceed the Stark widths of these lines with sufficient margin. The exit slits of the monochromators have equal widths, 0.8 mm. A control scanning of the measured spectral interval with the aid of the monochromator has shown no interference with the measurements of the intensities of the lines H_β and H_δ on the part of any other lines or the continuum. The plasma obtained, of course, also emits in the He I lines, the intensities of which are in reasonable correspondence with the intensities of the Balmer-series lines.

4. EXPERIMENTAL RESULTS

Before reporting the results, we must note once more that the circuit supplying the electron gun governed only the rising front of the beam pulse. The trailing edge of the beam was due to "short-circuiting" of the gun by the arrival of plasma from the working volume. This

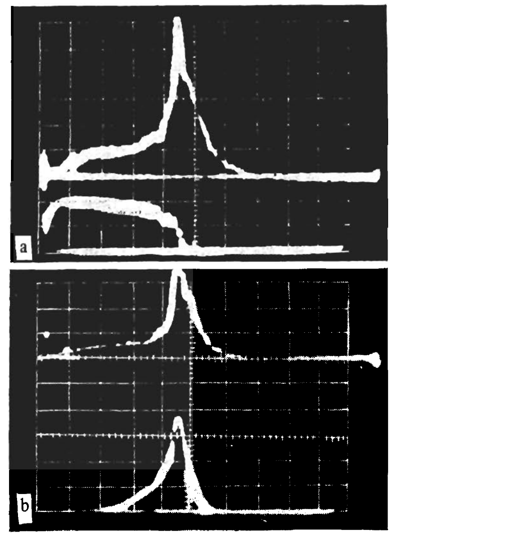


FIG. 2. Oscillograms of accelerating voltage (V), beam current (I), and intensity of the H_β spectral line. a—I (top) and V; b—I (top) and H_β. Sweep rate 50 μsec/div. The vertical scales of I are 15 A/div (a) and 35 A/div (b) and that of V is 5 kV/div. The hydrogen content in the He-H_2 mixture is 10%.

"feedback" on the part of the plasma led to a strong increase of the electron-beam current "drawn out" of the gun. As a result, the beam current and the electron-accelerating voltage varied in time as shown by the typical oscillograms in Fig. 2. We see that during the greater part of the pulse the beam current amounts to 10–15 A at an accelerating voltage 10 kV, and at the end of the pulse it increases by approximately one order of magnitude, and after reaching a maximum $I_{max} \approx 100-150$ A it decreases with a (rather large) characteristic time ~25 μsec. The absence of an abrupt trailing edge of the beam excludes the possibility of determining the characteristic plasma recombination time from the "afterglow" of the discharge: the time variation of the spectral-line intensity duplicates qualitatively the oscillogram of the beam current (Fig. 2). However, the "feedback" from the plasma to the electron gun makes it possible (owing to the increase of the beam current) to obtain larger plasma densities. All the subsequent measurements were carried out in the indicated beam regime. The magnetic field intensity in the working volume was 1200 Oe.

Figure 3a (curve 1) shows the contour of the H_β line corresponding to the instant t = 150 μsec from the start of the beam pulse (the maximum beam current is reached in this case at t = 220 μsec). We see that this contour has a typical Stark form. From the half-width of this contour (after subtracting the sum of the Doppler and apparatus half-widths, which equals ~0.6 Å) and from formula (11) we determined the plasma density $N_e = 1.6 \times 10^{15}$ cm^{-3}, and plotted for the obtained value of N_e the theoretical Stark profile of the H_β line (curve 2 of Fig. 3a); the total area bounded by this profile and the coordinate axes is the same as that of the experimental contour (curve 1). Comparison of curves 1 and 2 of Fig. 3a illustrates the rather good agreement between the experimental and theoretical contours of the H_β line. Some quantitative differences between them are due to the radial inhomogeneity of the plasma parameters and are quite unavoidable, since the plasma emission is observed through the plasma pinch. The described procedure of determining N_e gives the effective value of the plasma

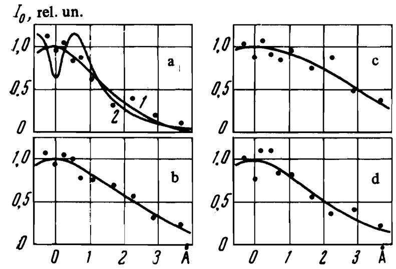


FIG. 3. Contour of H_β spectral line. The abscissas represent the displacements from the line center and the ordinates the light intensity I_i. The hydrogen content in the mixture is 10%. A) 1—Typical experimental contour plotted for the instant t = 150 μsec from the start of the beam pulse, plasma concentration $N_e = 1.6 \times 10^{15}$ cm^{-3}; 2—theoretical Stark contour of the H_β line at $N_e = 1.6 \times 10^{15}$ cm^{-3} and the same total contour area as for curve 1. b, c, d—experimental contours obtained with the same beam pulse as curve 1; b) t = 190 μsec; $N_e = 2.8 \times 10^{15}$ cm^{-3}; c) t = 220 μsec, $N_e = 4.6 \times 10^{15}$ cm^{-3}; d) t = 250 μsec, $N_e = 2.4 \times 10^{15}$ cm^{-3}.

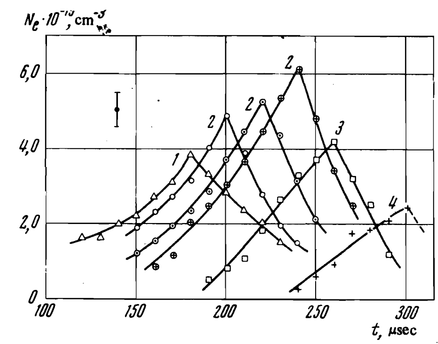


FIG. 4. Time dependence of the plasma density at different hydrogen contents in the He-H_2 mixture: 1—pure helium; 2—10% H_2; 3—25% H_2; 4—50% H_2. In the upper left corner is indicated the rms measurement error. The instants of the beam-current maxima coincide with the maxima of the plasma density.

concentration, averaged (in the indicated sense) over the cross section of the plasma pinch.

Contours analogous to Fig. 3a were measured at different instants of time within the duration of the beam pulse; some of them are shown in Figs. 3b, 3c, and 3d. These measurements show that the half-width of the H_β line decreases monotonically from 0.6 to 6–7 Å from the start of the discharge pulse to the instant of the maximum beam current. Formula (11) was used to construct the time dependence of the plasma density $N_e(t)$ from these measurements, as shown in Fig. 4. The different curves of Fig. 4 correspond to different hydrogen contents in the He-H_2 mixture: from "zero" (when the hydrogen atoms previously absorbed by the working-volume walls are knocked out from the walls by the plasma particles) to 50%. In the case of pure hydrogen (without helium), as already indicated, the half-width of the contour H_β is less than the registration threshold of the apparatus. Each of these curves of Fig. 4 constitutes the result of averaging of the functions $N_e(t)$ over a train of 4–6 beam pulses with one and the same duration. The characteristic error with which the time dependence of the plasma density is measured in Fig. 4 constitutes the rms deviation of the function $N_e(t)$, obtained in individual pulses of the series, from the function $N_e(t)$ averaged over the train.

It is seen from Figs. 3 and 4 that within the duration of the beam pulse the plasma density increases monotonically, and reaches, by the time the maximum beam current is attained, a value $N_e \approx 4 \times 10^{15}$ cm^{-3} in the case of pure helium and $N_e \approx 5 \times 10^{15}$ cm^{-3} in the case when 10% hydrogen is added to the helium; when the beam current decreases (after attaining the maximum) the plasma density decreases. It is also seen that the plasma density at the beam-current maximum increases with increasing current-pulse duration (curves 2 of Fig. 4 were obtained with pulses of different duration).

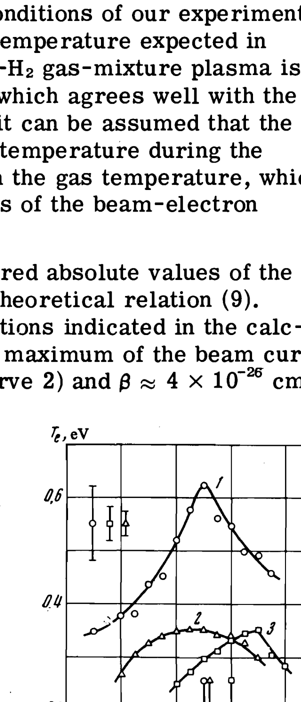
The plasma-electron temperature is determined from the oscillograms of the relative intensities of the H_β and H_δ lines; a typical oscillogram of the H_β line is shown in Fig. 2. The time dependence of the electron temperature is shown in Fig. 5 for three values of the hydrogen admixture in the He-H_2 mixture. The procedure for plotting the curves of Fig. 5 and for determining the rms measurement error is quite similar to that indicated in the description of Fig. 4. It is seen from Fig. 5 that the plasma-electron temperature increases monotonically during the discharge pulse, reaches a maximum at the instant of the beam-current maximum, and then decreases. In pure helium, T_e amounts to ~0.4 eV at the middle of the discharge pulse and ~0.6 eV at the instant of the maximum beam current. Addition of 10–30% of molecular hydrogen to the helium lowers the electron temperature by approximately one-half. This agrees with the mechanism of dissociative thermal conductivity of the gas in the presence of an impurity, which was mentioned in Sec. 1. This mechanism, as already indicated, can stabilize the He-H_2 gas mixture temperature at a level $T \lesssim 0.2-0.3$ eV under the considered experimental conditions. The deviation ΔT_e between the electron temperature and the gas temperature can be determined from (7). If we use in (7) the parameters typical of our experiments, namely $N_0 = 2 \times 10^{18}$ cm^{-3}, $\sigma_1 = 2 \times 10^{-18}$ cm^2 (W_1 = 10 keV), and $N_e \approx 5 \times 10^{15}$ cm^{-3}, and if $I \approx 120$ A (the instant of the beam-current maximum) and $N_1 v_1 \approx 7 \times 10^{20}$ cm^{-2} sec^{-1}, and if we use the values of $\langle \sigma_{el} v_e \rangle$ and $\langle \sigma_C v_e \rangle$ indicated in Sec. 1, then we obtain from (7)

$$\Delta T_e \approx 10^{-1} \text{ eV}. \tag{7'}$$

Consequently, under the conditions of our experiments, (Figs. 4 and 5), the electron temperature expected in accordance with (7′) in an He-H_2 gas-mixture plasma is $T_e = T + \Delta T_e \approx 0.3-0.4$ eV, which agrees well with the measurement results. Thus, it can be assumed that the (slow) growth of the electron temperature during the beam pulse is due to a rise in the gas temperature, which results from the larger losses of the beam-electron energy to ionization.

Let us compare the measured absolute values of the plasma parameters with the theoretical relation (9). Under the experimental conditions indicated in the calculation of (7′), we have at the maximum of the beam current $T_e \approx 0.35$ eV (Fig. 5, curve 2) and $\beta \approx 4 \times 10^{-26}$ cm^6

FIG. 5. Time dependence of the plasma electron temperature at different hydrogen contents in the He-H_2 mixture: 1—pure helium, 2—10% H_2, 3—25% H_2. In the upper left corner are indicated the rms measurement errors. The vertical bars in the central part of the figure indicate the instants of the maxima of the beam current in pulses with different H_2 contents.



sec^{-1}[2a], and we obtain from (9) $N_e \approx 4 \times 10^{15}$ cm^{-3}, which practically coincides with the plasma density measured at the considered instant of time (Fig. 4, curves 2). The increase in the plasma-electron temperature during the course of the beam pulse (Fig. 5) causes, as a result of the decrease of the recombination coefficient $\beta(T_e)$[2], a monotonic increase in the plasma concentration up to the instant of the maximum of the beam current (Fig. 4), and also an increase in the maximum density with increasing current duration (Fig. 4, curves 2).

It is important to note that the characteristic plasma recombination time τ_{rec} at the instant of the maximum beam current in the He-H_2 mixture ($N_e \approx 5 \times 10^{15}$ cm^{-3}, T_e = 0.35 eV) is $\tau_{rec} \approx 1/N_e^2\beta \approx 1$ μsec, which is smaller by more than two orders of magnitude than the beam-pulse duration. This means that a stationary recombination regime is physically realized under the considered experimental conditions.

Returning now to the formulation of the problem, it is of interest to compare the experimentally obtained plasma parameters (Figs. 4 and 5) with the criterion stipulated in the Introduction for the supercooling of plasma electrons, i.e., to compare the obtained values of N_e, T_e, and N_n with the thermodynamic-equilibrium values $(N_e)_{eq}$ and $(N_n)_{eq}$, determined by the formulas of Saha (1) and Boltzmann (2).

We make this comparison first for the instant of time t = 170 μsec from the start of the beam pulse. Turning to curves 1 of Figs. 4 and 5, we have for the indicated instant of time, in the case of a pure helium plasma (without a hydrogen admixture) T_e = 0.4 eV and $N_e \approx 3 \times 10^{15}$ cm^{-3}; according to formula (3), the concentration of the excited atoms in the state n = 4 is equal in this case to $N_4 \approx 3 \times 10^{11}$ cm^{-3} ($N_0 \approx 2 \times 10^{18}$ cm^{-3}). According to formulas (1) and (2), a helium-plasma temperature T_{eq} = 0.4 eV corresponds to the thermodynamic-equilibrium concentrations of the free electrons and excited atoms $(N_e)_{eq} \approx 10^4$ cm^{-3} and $(N_4)_{eq} \approx 10^{-6}$ cm^{-3}, respectively. Consequently, the experimentally measured values of N_e and N_4 exceed the thermodynamic-equilibrium values by more than 11 and 17 (!) orders of magnitude, respectively. The experimentally-measured electron temperature T_e = 0.4 eV is smaller by a factor of more than three than the thermodynamic-equilibrium temperature T_{eq}, which, according to Saha's formula (1), corresponds to the measured helium-plasma density $N_e \approx 3 \times 10^{15}$ cm^{-3} at $N_0 = 2 \times 10^{18}$ cm^{-3}.

Let us return to the instant of the beam-current maximum when we have in a helium plasma (without the hydrogen added) $T_e \approx 0.6$ eV, $N_e \approx 4 \times 10^{15}$ cm^{-3}, and $N_4 \approx 2 \times 10^{10}$ cm^{-3}. It is easy to see that at this instant we have $T_e \lesssim 0.5\, T_{eq}$, $N_e \approx 4 \times 10^6 (N_e)_{eq}$, and $N_4 \approx 2 \times 10^7 (N_4)_{eq}$.

Thus, in our experiments we have obtained a deeply supercooled stationarily-recombining, weakly-ionized helium "beam" plasma, the parameters of which can easily be regulated. The range of variation of the plasma parameters corresponds approximately to the feasibility of experimental verification of the idea of a stationary recombination (plasma) laser[3]. We are presently undertaking such a verification.

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